Hard-Scattering Results from PHENIX

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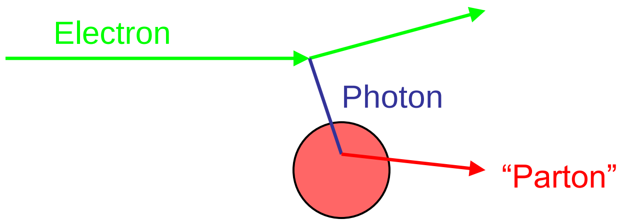
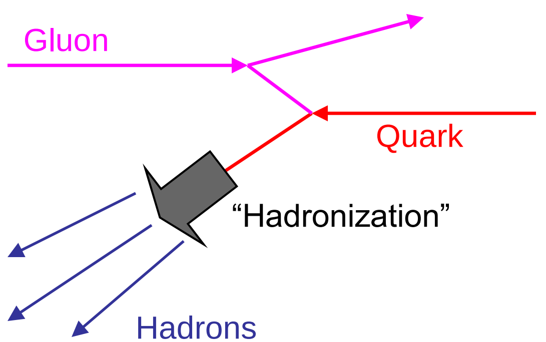
Hard Scattering: Point-like QCD objects undergoing scatterings with high momentum transfer



Early 1970's: Deep inelastic scattering identifies point-like "partons" within nuclei.

QCD theory of strong interactions suggests partons are quarks. If so, then quarks and gluons should have point-like scatterings with each other in hadron collisions:



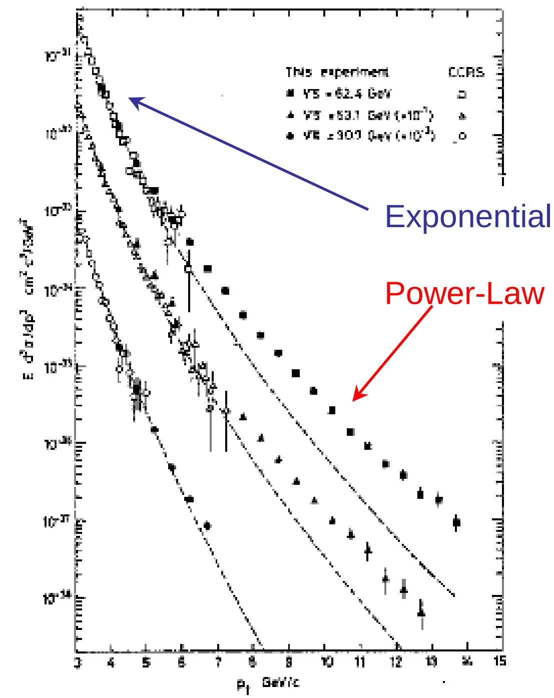
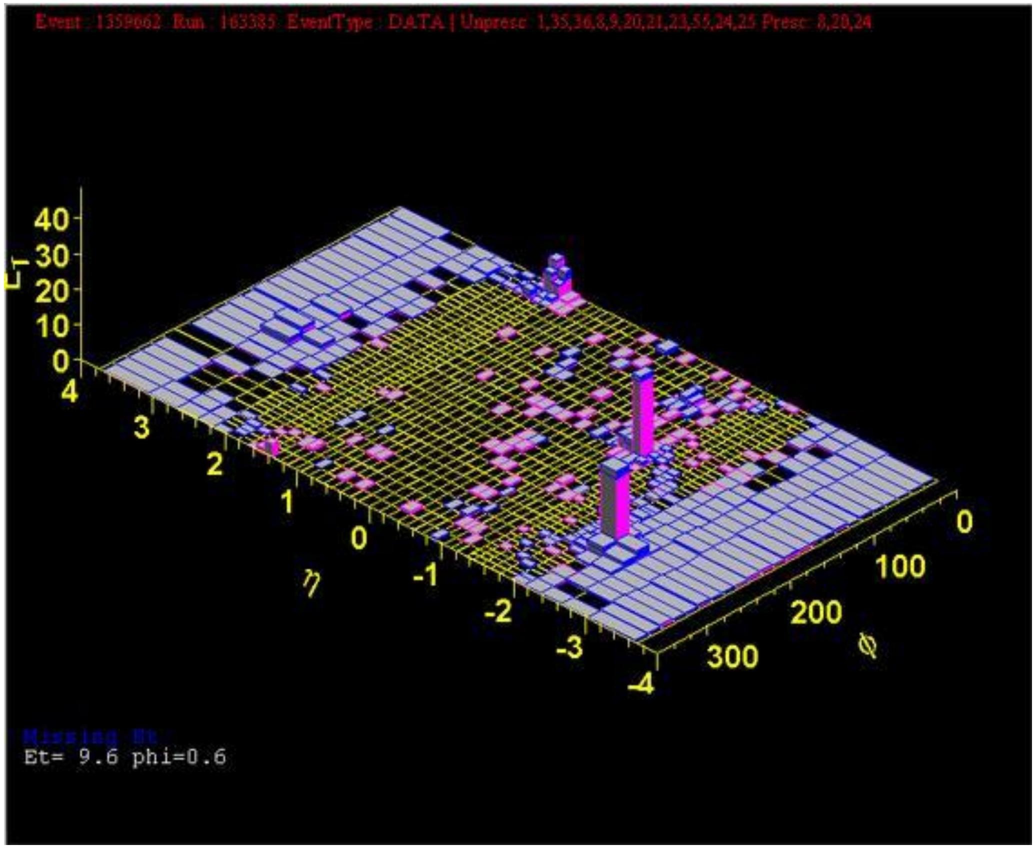


Figure 13: CCOR transverse momentum dependence of the invariant cross section for $p - p \to \pi^0 + X$ at three center of mass energies. Cross sections are offset by the factors noted. Open points and dashed fit are from a previous experiment, CCRS, F. W. Büsser, et al., Nucl. Phys. B106, 1 (1976).

Late 1970's: Tell-tale sign of point-like scatterings would be a power-law behavior in spectrum of produced hadrons. This is revealed once high enough energy becomes available.

Defining “QCD Hard Scattering” con’t



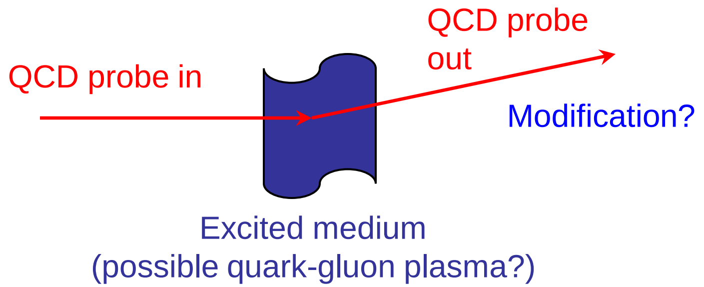
Early 1980’s -- Present:
Localized deposit of hadronic energy into a small angular cone -- a “jet” -- is indentified as the observable end product of a hard-scattered quark or gluon.

From this time on, the “calorimetric jet” becomes *the* standard proxy for having observed a quark or a gluon produced in a high-energy collision.

How do we use hard-scattering processes in relativistic heavy-ion physics?

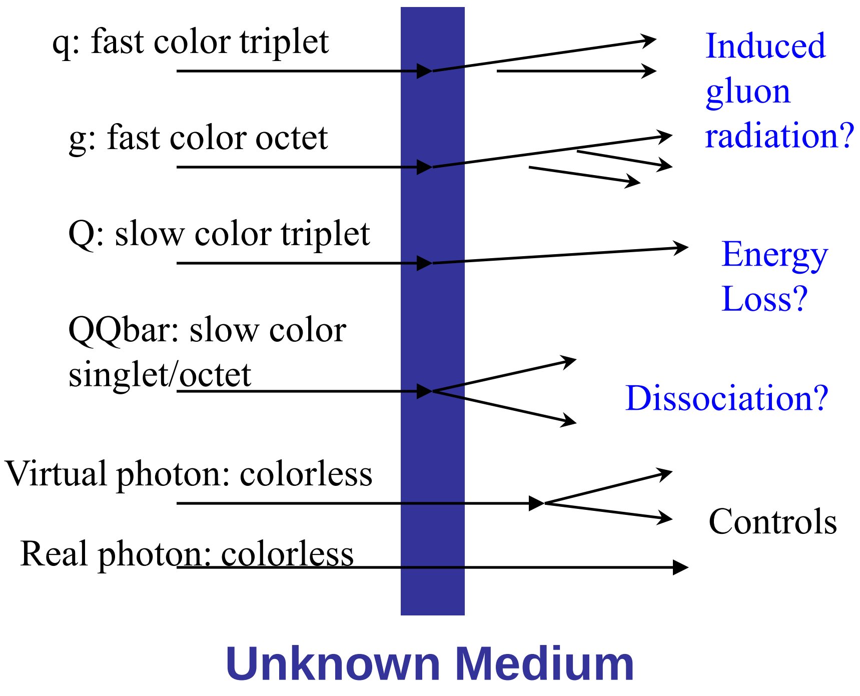
High-Energy Heavy-Ion Physics (in Brief)

A **main goal** of relativistic heavy ion physics is to investigate **high-temperature, high-density QCD**, by creating and then studying the **highly-excited medium** produced in high-energy nuclear collisions.

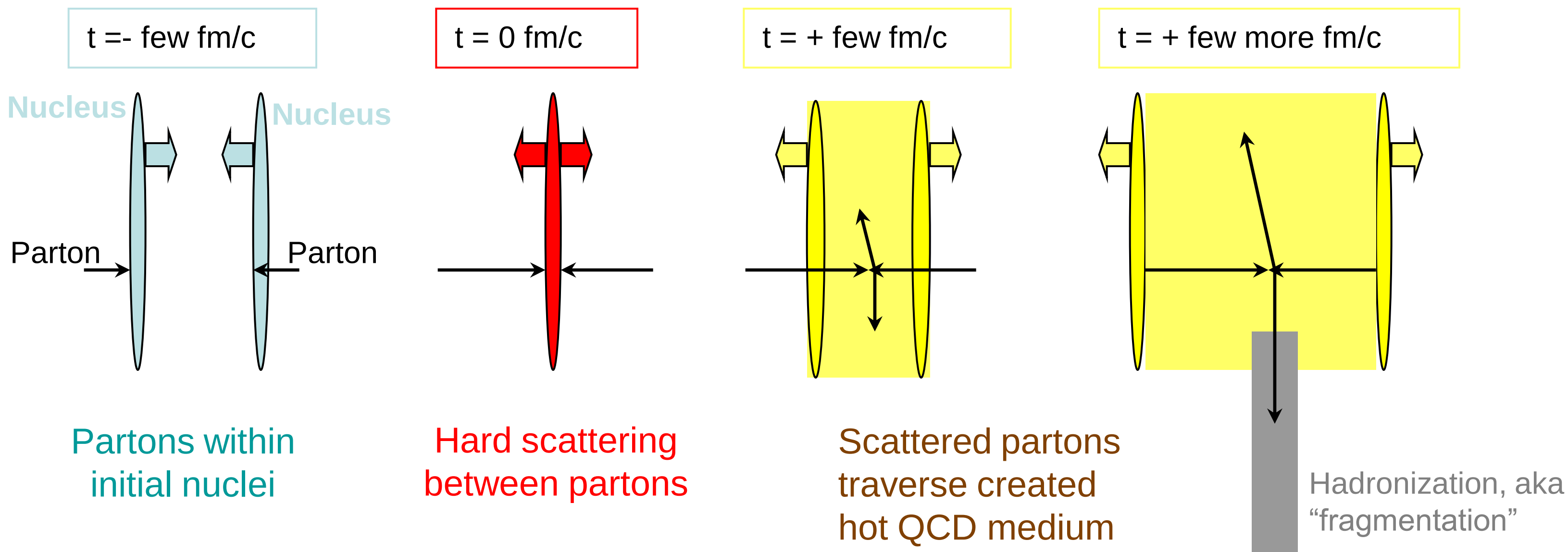


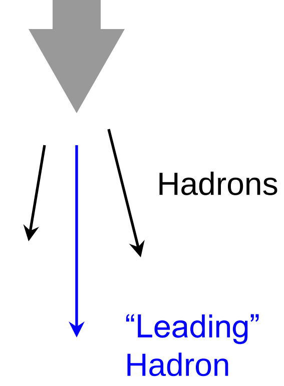
One method of diagnosing a QCD medium is to shoot a QCD-sensitive probe through it, then look for any modifications due to the medium. (Most obvious possibilities: multiple scatterings, induced radiations, and energy loss.)

The full pallet of QCD probes can be created and measured in the PHENIX experiment



Hard-scattered partons are built-in QCD probes within RHI collisions





We measure high-P_T leading hadrons.
Two basic things we look for:

1) If scattered partons lose energy, the number of leading hadrons at high Pt will be depleted (suppressed)

2) If the fragmentation process is modified, the ratios between different types of produced particles (π,K,p) may change.

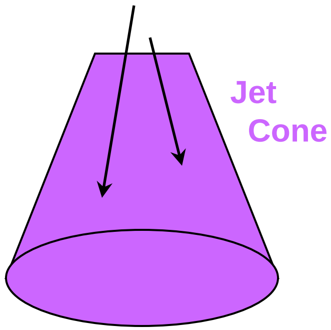
Leading Hadrons vs Calorimetric Jets

- Cannot look at "true", traditional calorimetric jets; soft particle energy density $dE_T/d\eta d\phi \sim 100$ GeV/unit-radian

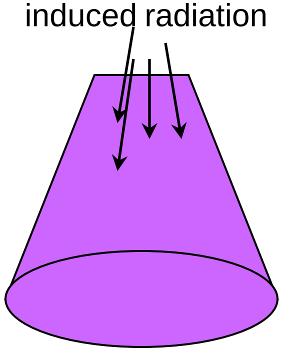
- Next best thing: leading particles = high-P_T hadrons, and also high-P_T pairs, either same side (leading and next-leading) or opposite side (leading and opposite leading)

- In some ways, leading particles are a better measure of nuclear medium effects! since induced gluon radiation might change the total energy in small-angle cone.

Particles, no induced radiation



Particles with induced radiation



More particles, each lower energy; but total energy **unchanged**

History of High-Energy A+A Beams

- **BNL-AGS**: mid 80's, early 90's

  O+A, Si+A 15 AGeV/c $s^{1/2}_{NN}$ ~ **6 GeV**

  Au+A 11 AGeV/c $s^{1/2}_{NN}$ ~ **5 GeV**

- **CERN-SPS**: mid 80's, early 90's

  O+A, S+A 200 AGeV/c $s^{1/2}_{NN}$ ~ **20 GeV**

  Pb+A 160 AGeV/c $s^{1/2}_{NN}$ ~ **17 GeV**

- **BNL-RHIC**: early 00's

  Au+Au $s^{1/2}_{NN}$ ~ **130 GeV**

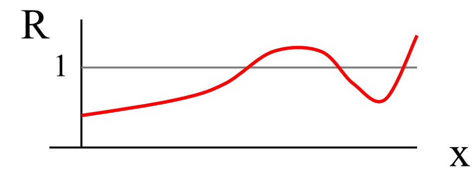
  Au+Au, p+p $s^{1/2}_{NN}$ ~ **200 GeV**

Finally: enough energy for copious hard scattering processes!

Quantifying Nuclear Effects

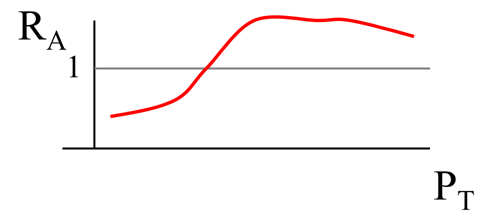
$R = \sigma_{eA}(x,Q^2)/A\,\sigma_{ep}(x,Q^2)$ General DIS

Shadowing, EMC, etc.



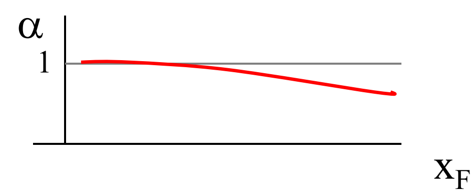
$R_A = \sigma_{pA}(P_T)/A\,\sigma_{pp}(P_T)$ Hadron P_T spectra

Cronin effect



$\sigma_{pA}(x_F) = A^{\alpha}\,\sigma_{pp}(x_F)$ eg DY, J/Ψ

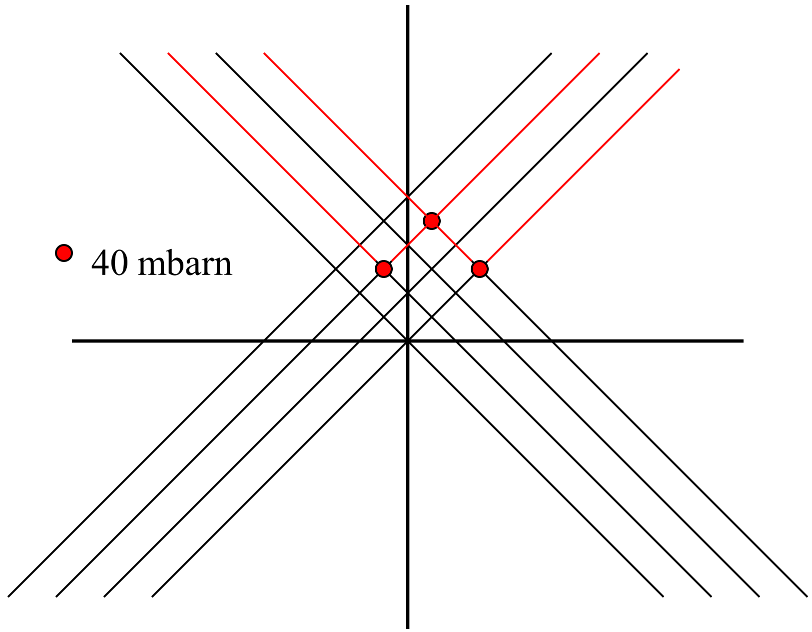
Absorption, initial state energy loss



$$R_{AA}(p_T) = \frac{\langle N_{binary}\rangle (d^2\sigma^{pp}/dp_T d\eta)/\sigma^{pp}_{inelastic}}{1/N_{events}\; d^2N_{AA}/dp_T d\eta}$$ A+A hadrons **?**

(This space available!)

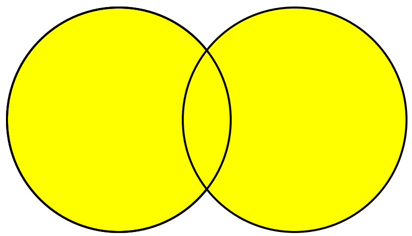
Nomenclature: Centrality



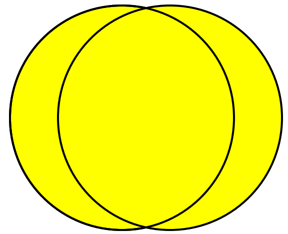
Characterize A+A collision intuitively in Glauber model:
Here $N_{Participant} = 4$
$N_{Collision} = 3$

$<N_{Coll}> = <T_{AB}> \sigma_{N+N\ inel}$

Describe classes of events by percentile of impact parameter distribution:



Peripheral; 60%-80%
$<N_{Collisions}> = 20$ +- 5



Central; 0%-10%
$<N_{Collisions}> = 850$ +- 20

A closer look at the Nuclear Modification Factor R_{AA}

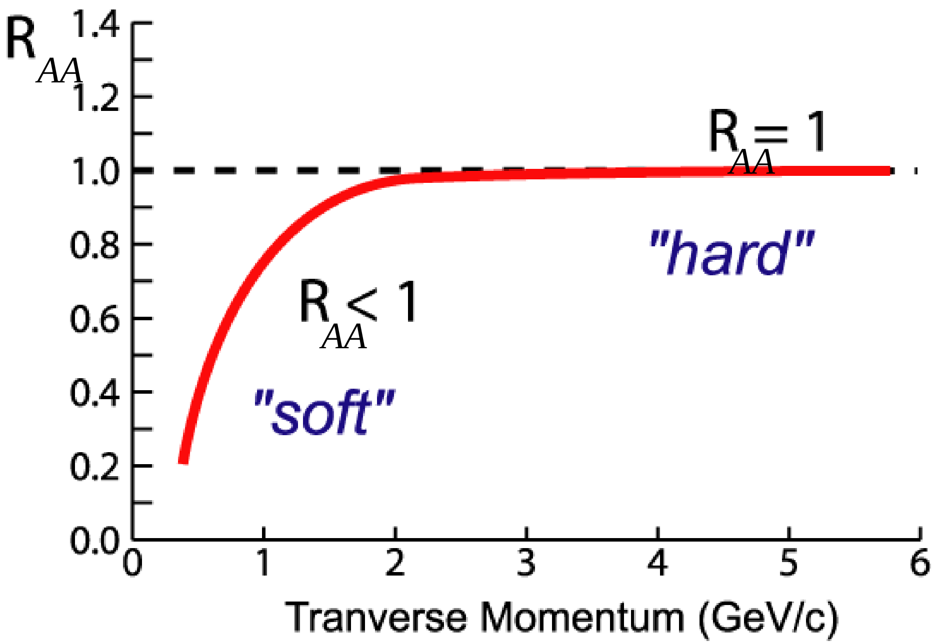
1. Compare Au+Au to nucleon-nucleon cross sections
2. Compare Au+Au central/peripheral

Nuclear Modification Factor:

$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d\eta}{T_{AA} d^2\sigma^{NN} / dp_T d\eta}$$

nucleon-nucleon cross section

$<N_{binary}>/\sigma_{inel}^{p+p}$



If no "effects":

$R_{AA} < 1$ in regime of soft physics

$R_{AA} = 1$ at high-p_T where hard scattering dominates

Suppression:

$R_{AA} < 1$ at high-p_T

The PHENIX Detector: Central Arms

The **PHENIX experiment** has many components and many capabilities, far more than can be described here.

Will mention one particular strength of PHENIX for hard-scattering physics: we can reconstruct both charged hadrons and neutral pions out to high PT.

(All RHIC data shown here were measured with PHENIX)

PHENIX

12 Countries; 57 Institutions; 460 Participants

Brazil
University of São Paulo, São Paulo

China
Academia Sinica, Taipei, Taiwan
China Institute of Atomic Energy, Beijing
Peking University, Beijing

France
LPC, University de Clermont-Ferrand, Clermont-Ferrand
Dapnia, CEA Saclay, Gif-sur-Yvette
IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
SUBATECH, Ecòle des Mines at Nantes, Nantes

Germany
University of Münster, Münster

Hungary
Central Research Institute for Physics (KFKI), Budapest
Debrecen University, Debrecen
Eötvös Loránd University (ELTE), Budapest

India
Banaras Hindu University, Banaras
Bhabha Atomic Research Centre, Bombay

Israel
Weizmann Institute, Rehovot

Japan
Center for Nuclear Study, University of Tokyo, Tokyo
Hiroshima University, Higashi-Hiroshima
KEK, Institute for High Energy Physics, Tsukuba
Kyoto University, Kyoto
Nagasaki Institute of Applied Science, Nagasaki
RIKEN, Institute for Physical and Chemical Research, Wako
RIKEN-BNL Research Center, Upton, NY
University of Tokyo, Bunkyo-ku, Tokyo
Tokyo Institute of Technology, Tokyo
University of Tsukuba, Tsukuba
Waseda University, Tokyo

S. Korea
Cyclotron Application Laboratory, KAERI, Seoul
Kangnung National University, Kangnung
Korea University, Seoul
Myong Ji University, Yongin City
System Electronics Laboratory, Seoul Nat. University, Seoul
Yonsei University, Seoul

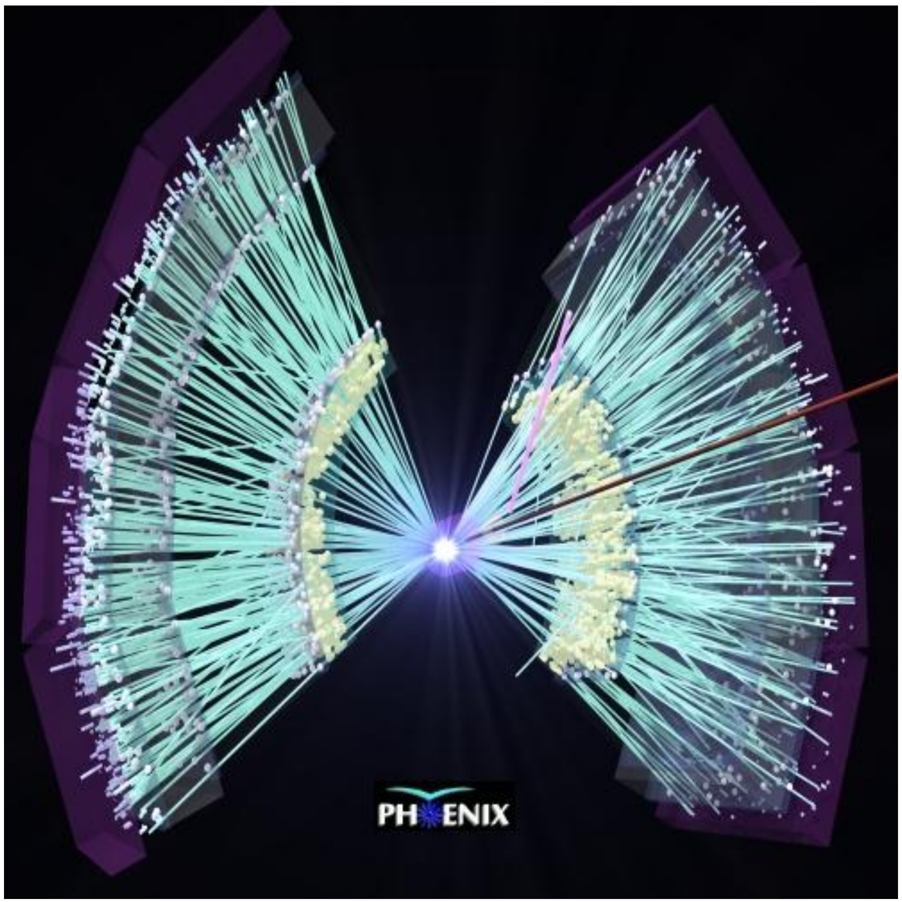
Russia
Institute of High Energy Physics, Protovino
Joint Institute for Nuclear Research, Dubna
Kurchatov Institute, Moscow
PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
St. Petersburg State Technical University, St. Petersburg

Sweden
Lund University, Lund

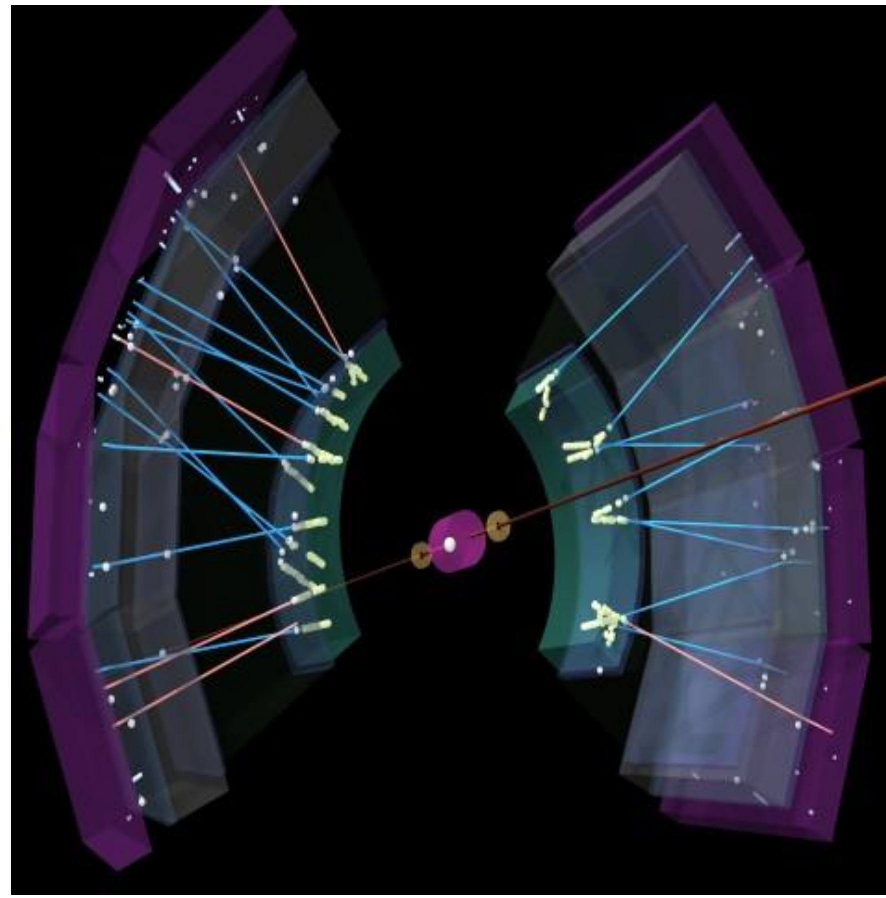
USA
Abilene Christian University, Abilene, TX
Brookhaven National Laboratory, Upton, NY
University of California - Riverside, Riverside, CA
University of Colorado, Boulder, CO
Columbia University, Nevis Laboratories, Irvington, NY
Florida State University, Tallahassee, FL
Georgia State University, Atlanta, GA
University of Illinois Urbana Champaign, IL
Iowa State University and Ames Laboratory, Ames, IA
Los Alamos National Laboratory, Los Alamos, NM
Lawrence Livermore National Laboratory, Livermore, CA
University of New Mexico, Albuquerque, NM
New Mexico State University, Las Cruces, NM
Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
Oak Ridge National Laboratory, Oak Ridge, TN
University of Tennessee, Knoxville, TN
Vanderbilt University, Nashville, TN

Two Collisions as seen by the PHENIX Central Arms

2001/2002 Au-Au



2001/2002 d-Au

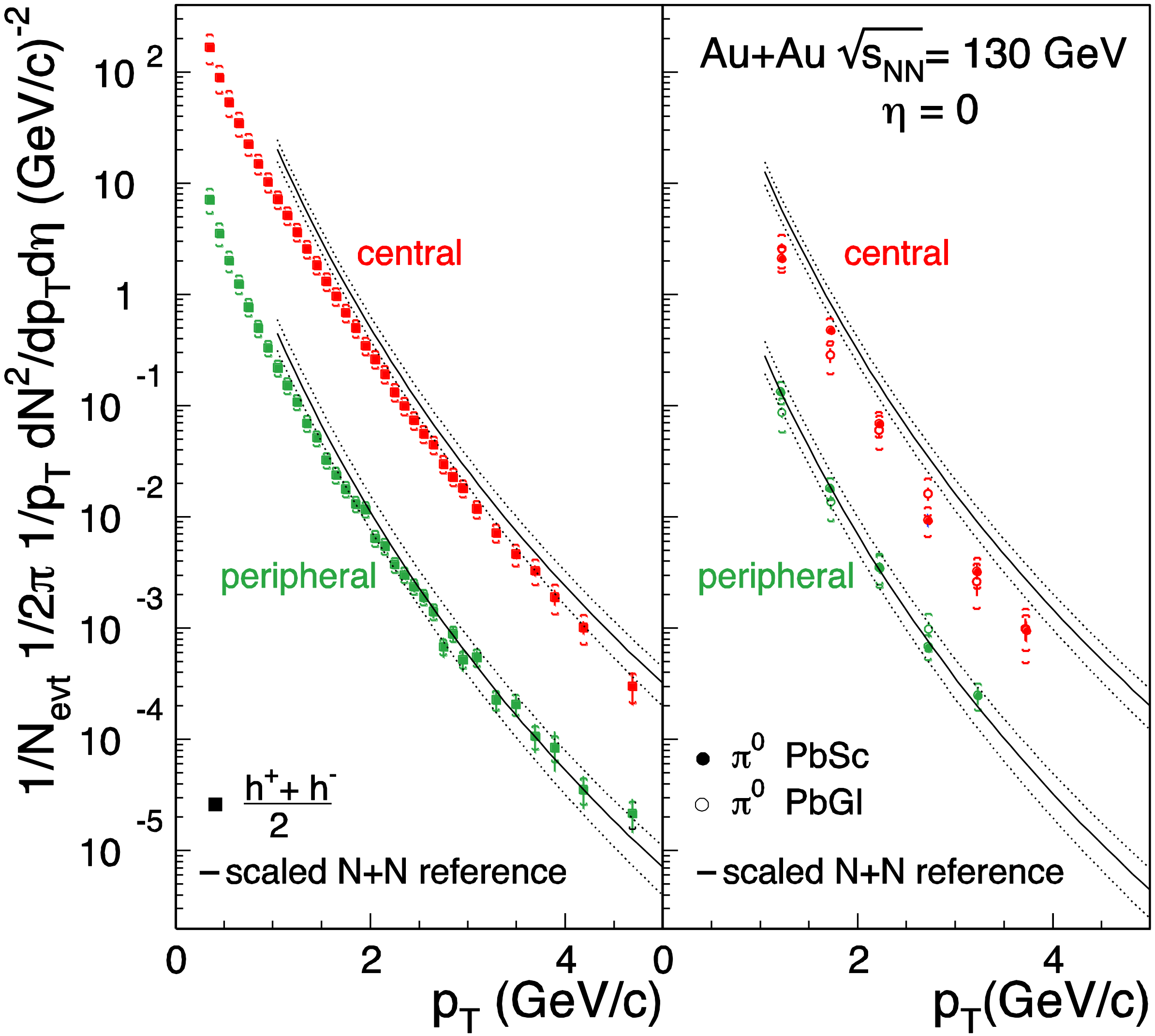


RHIC Year-1 High-P_T Hadrons

Charged and neutral hadron spectra out to p_T~4-5 GeV/c

Nominally expect production through hard scattering, scale spectra from N+N by number of binary collisions

Peripheral reasonably well reproduced; but central significantly below binary scaling



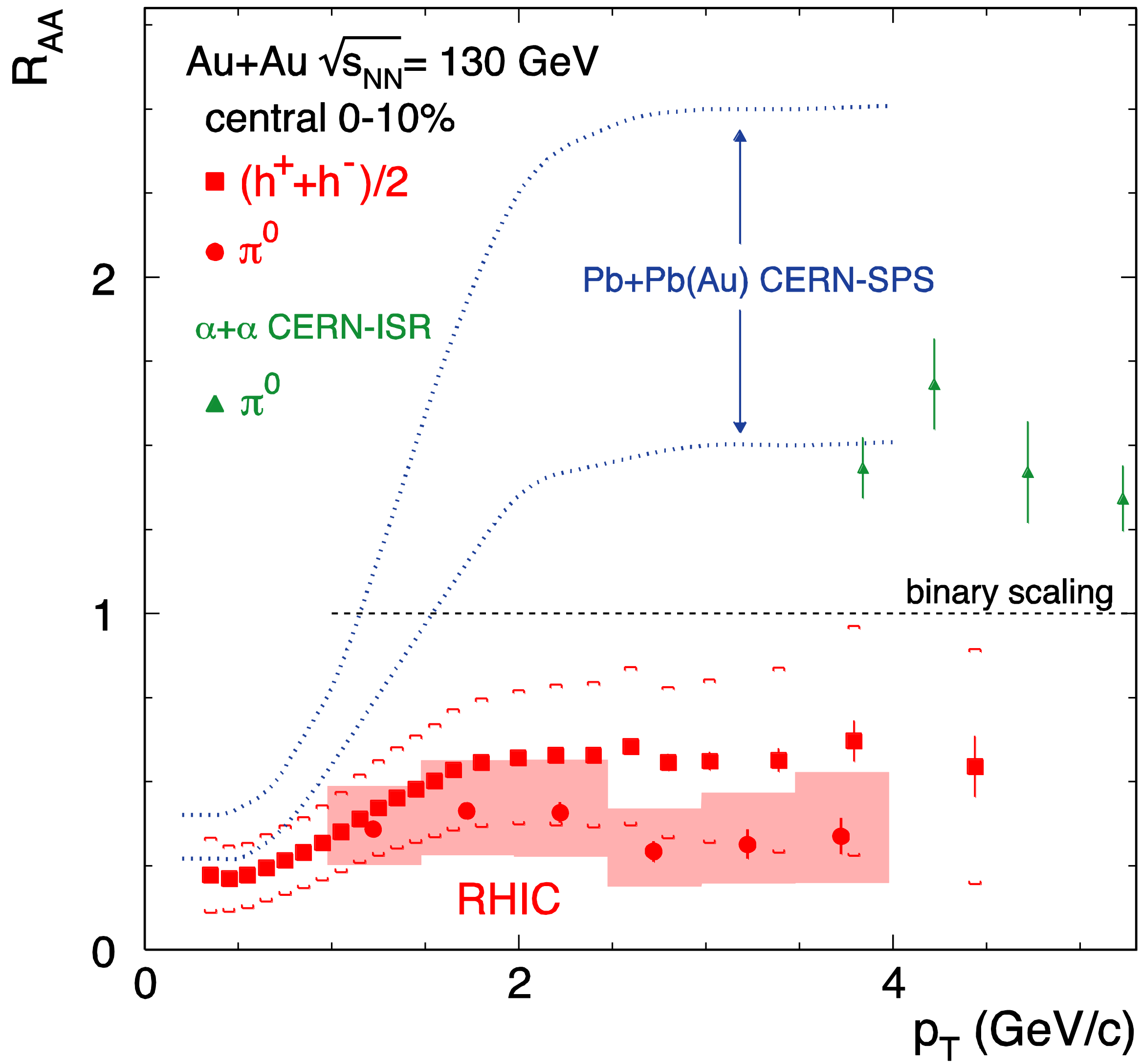
Last Year's Big News

Observe:

RHIC spectra fall below binary scaling at all p_T for central events

Previous highest energy A+A collisions exceed binary scaling (Cronin expectation)

Suspect: scattered parton interaction in dense medium; **but** must keep an open mind



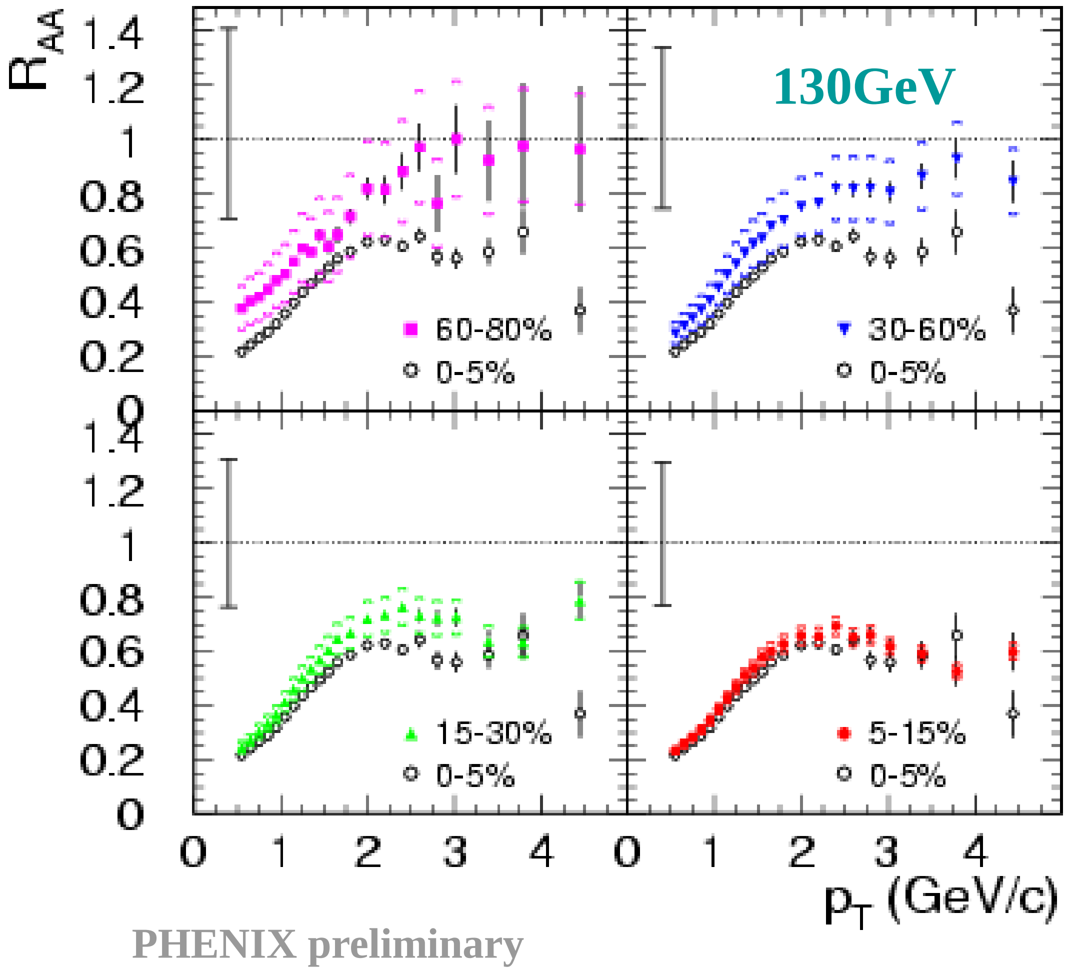
“The cover of the Rolling Stone”

(Almost) No one reads PRL on paper these days.

Cover artists thought the graph looked better without numbers on the axes.

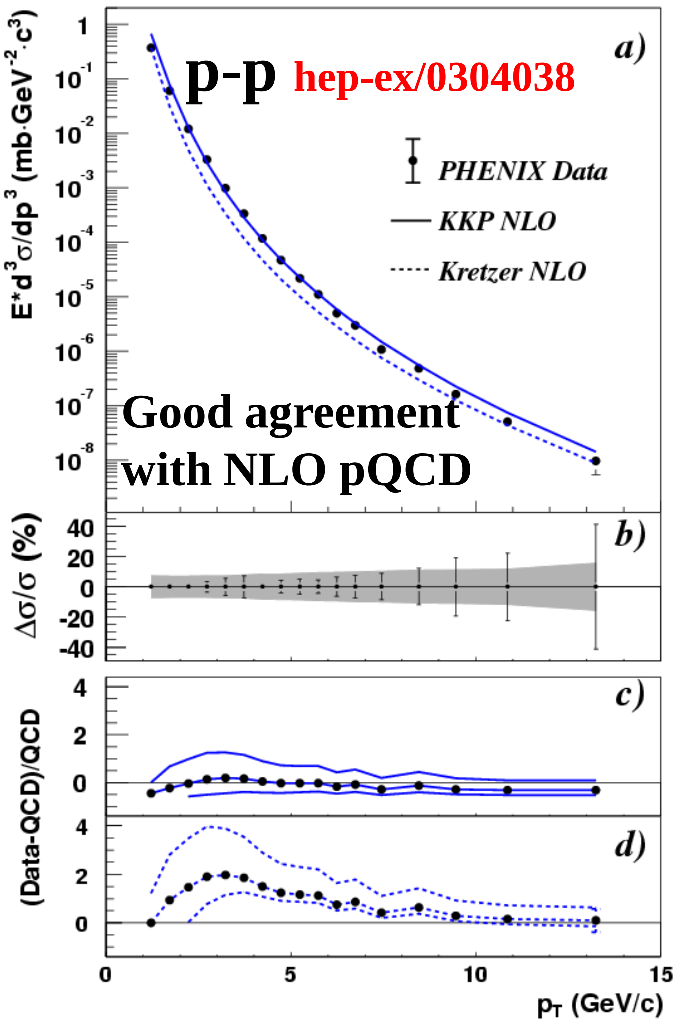
(We were pleased nonetheless.)

Onset of suppression is gradual with increasing collision centrality



Nuclear modification factor R_{AA} for charged particles in different centrality ranges in Au+Au collisions at 130GeV (result for most central collisions shown on all panels).

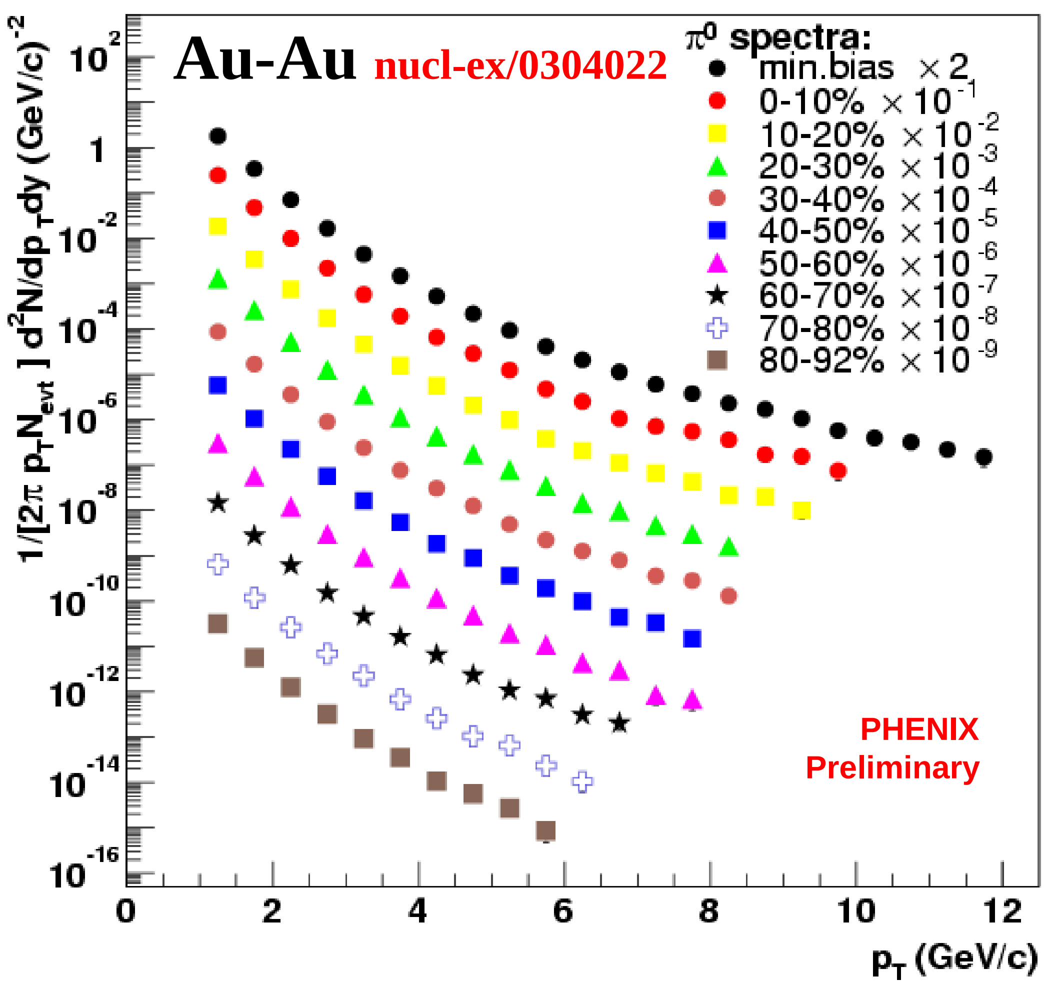
High-PT spectra now measured in p+p collisions at RHIC full energy

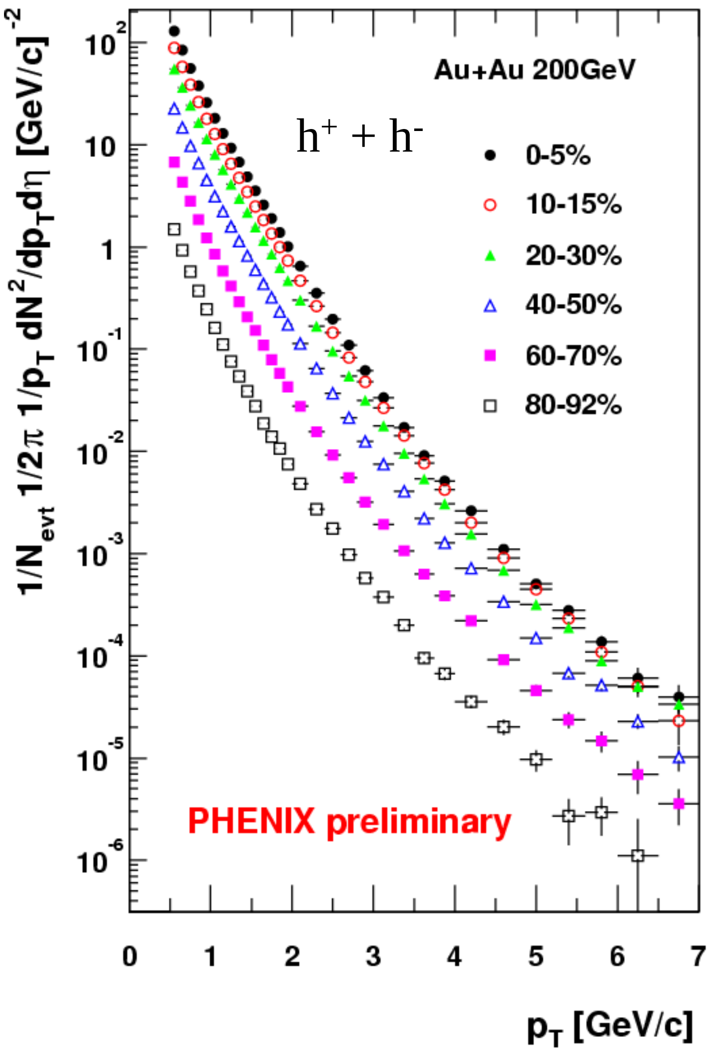


Spectra for π^0 out to 12 GeV/c are shown and compared to a NLO perturbative QCD prediction.

We have made direct contact with pQCD in highest-energy elementary p+p collisions!

Hadron spectra from full-energy RHIC Au+Au collisions now extend to higher P_T

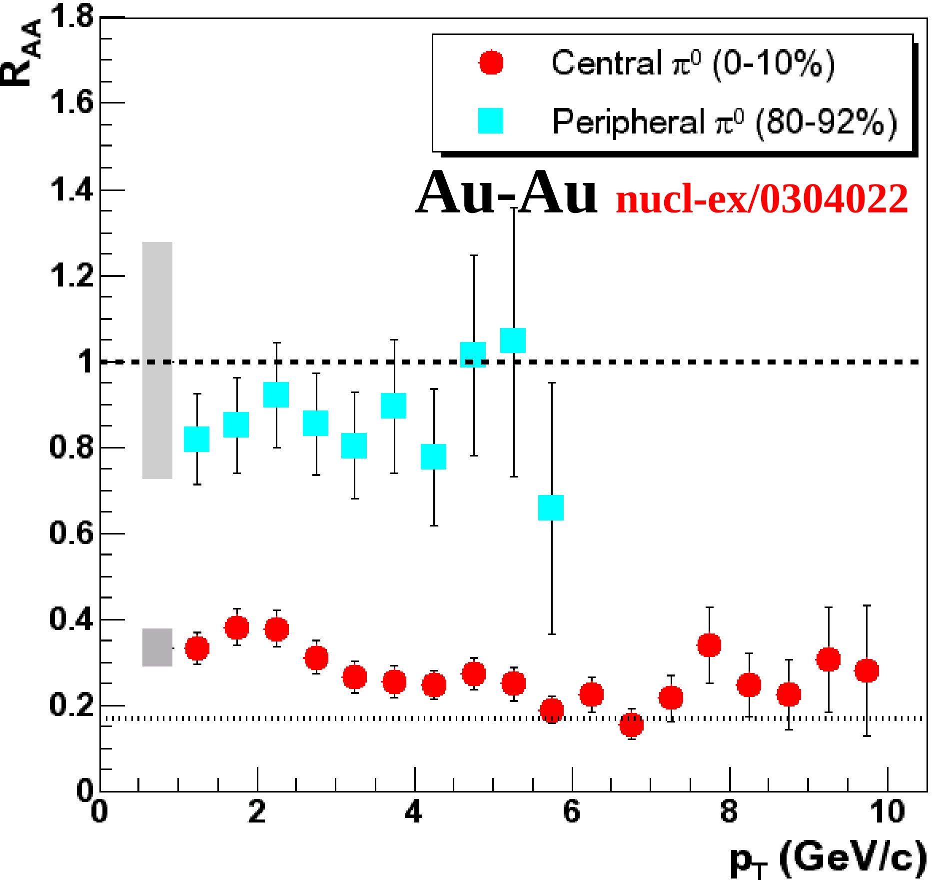


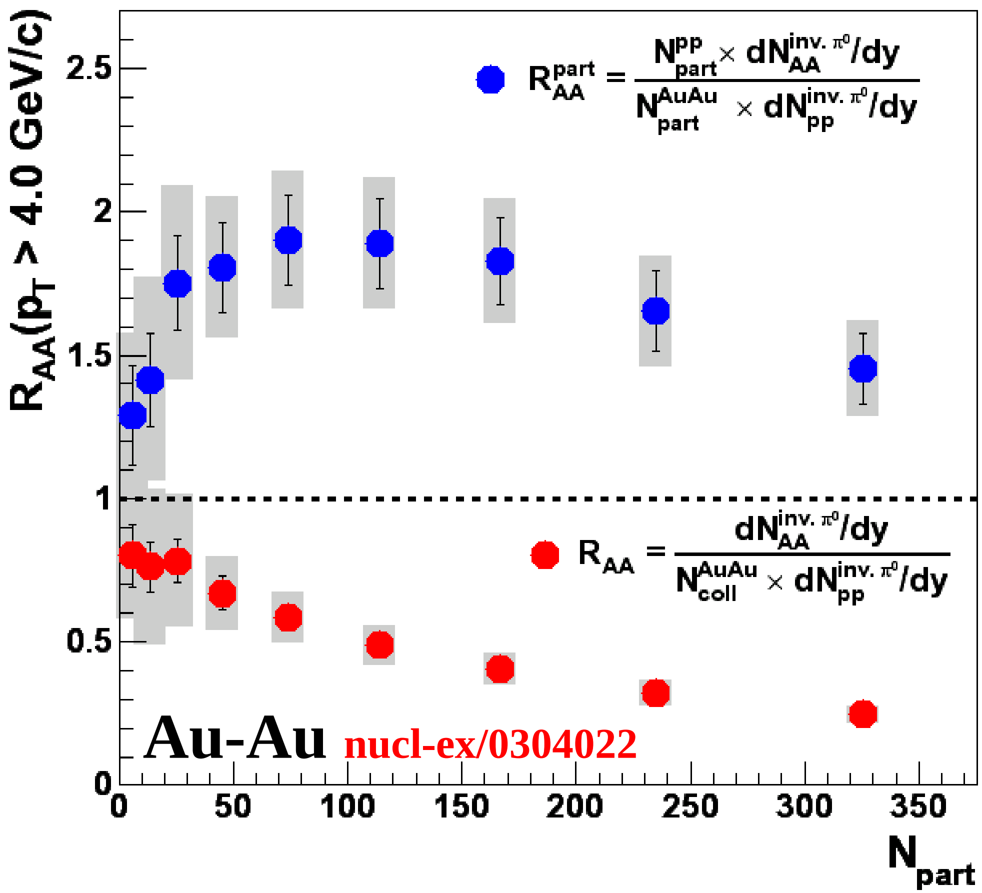


R_{AA}: High P_T Suppression continues in 200 GeV data out to at least 10 GeV/c

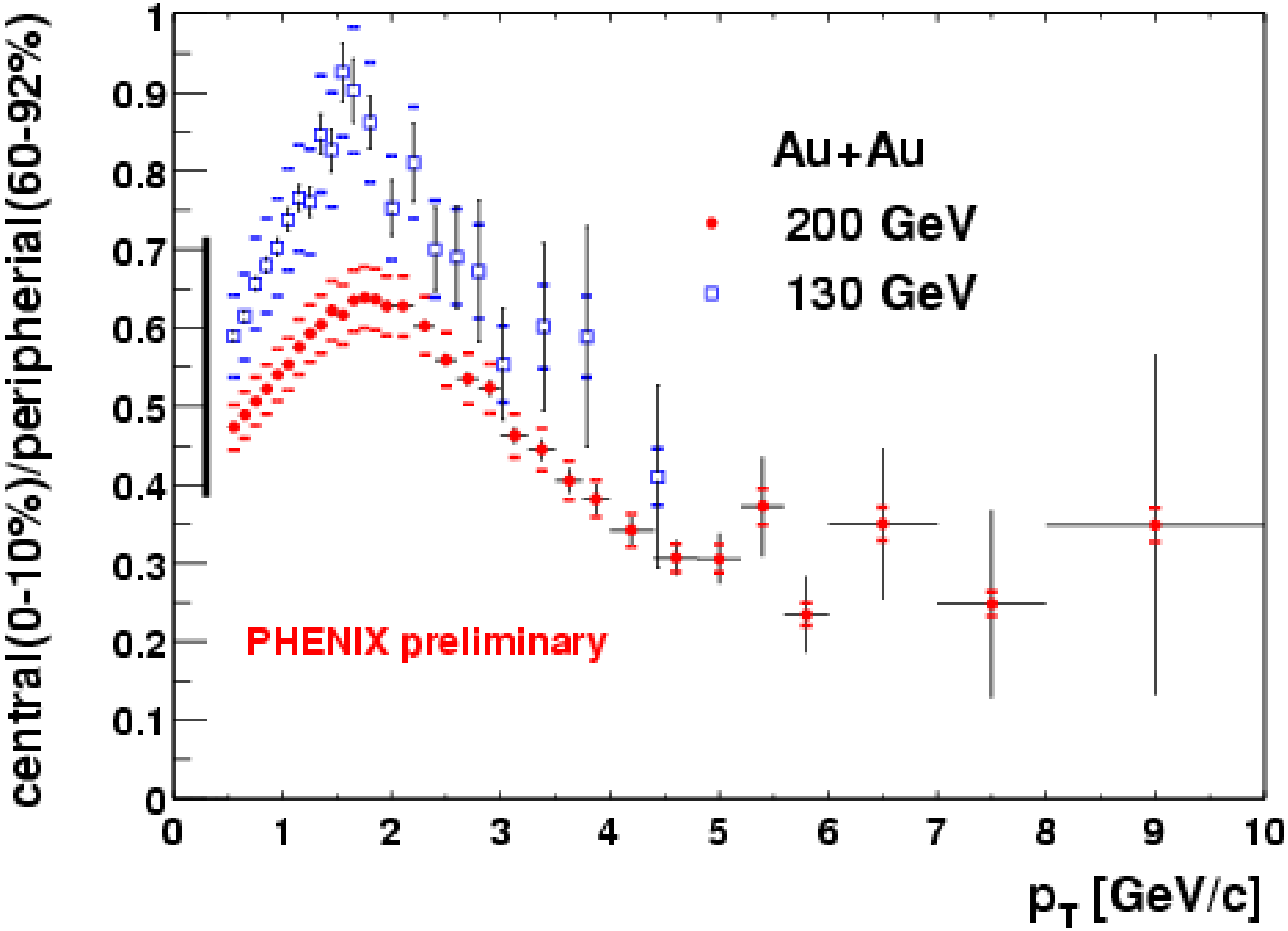
$$R_{AA} = \frac{\text{Yield}_{AuAu} / \langle N_{binary} \rangle_{AuAu}}{\text{Yield}_{pp}}$$

$$R_{AA}^{part} = \frac{\text{Yield}_{AuAu} / \langle N_{part} \rangle_{AuAu}}{\text{Yield}_{pp} / 2}$$





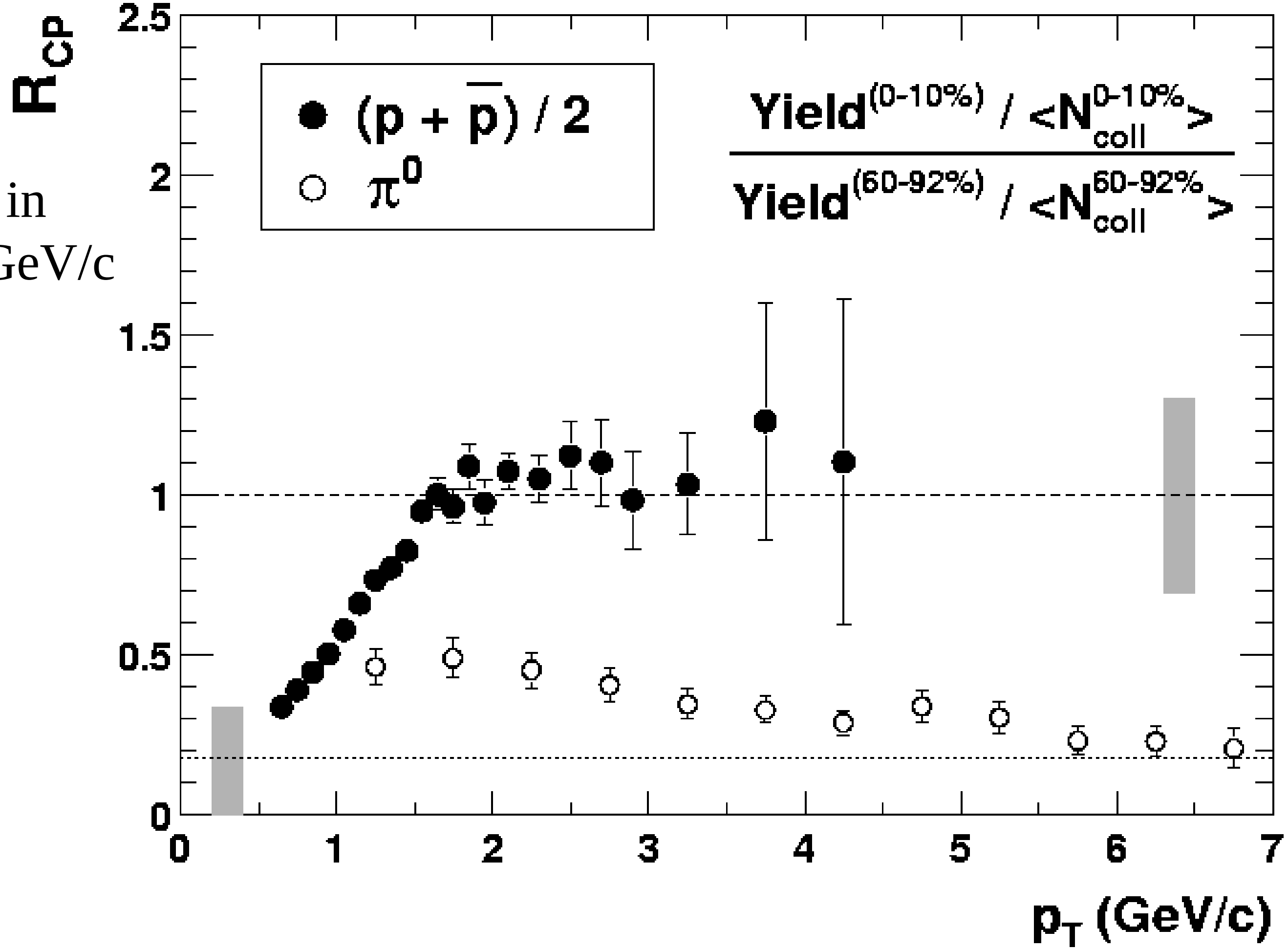
The Central/Peripheral ratio of spectra is another measure of nuclear modification



- Lower ratio for 200 GeV
  - more suppression or change in proton yield?
- Similar shape for 130 and 200 GeV
  - increase to 2 GeV/c
  - decrease to 4 GeV/c

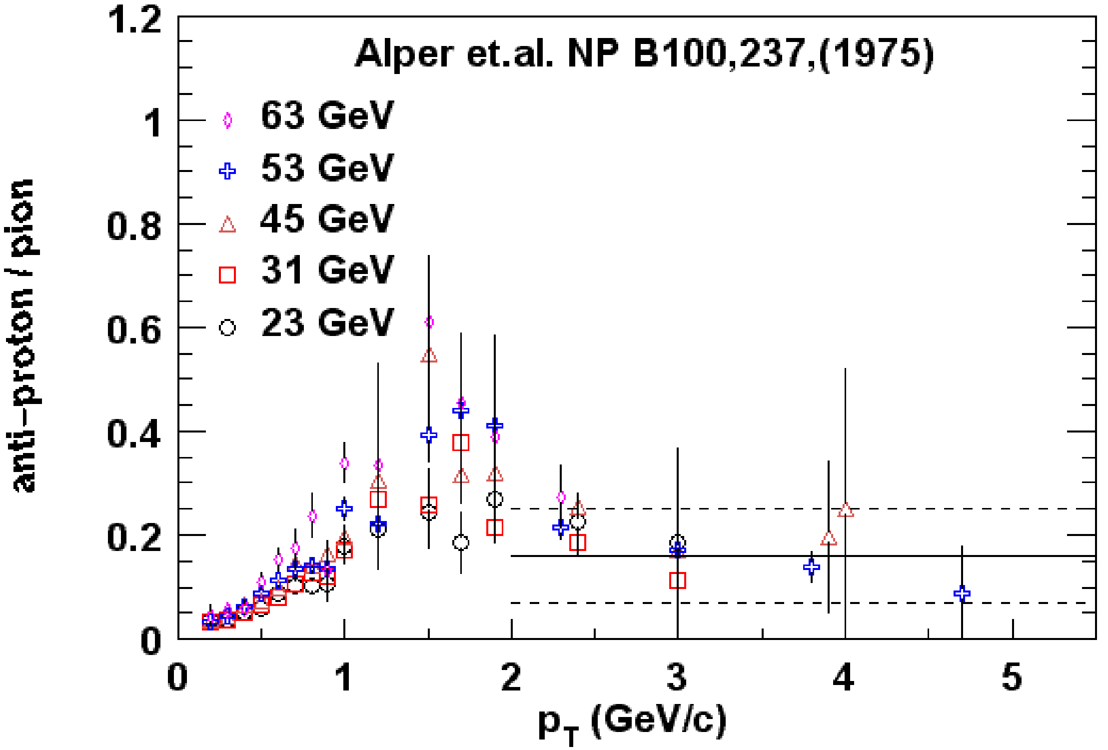
Central/Peripheral Ratio for (Anti)Protons and Pions

- No apparent suppression in proton yields for 2 <p_T<4 GeV/c
- Different production mechanism for protons?



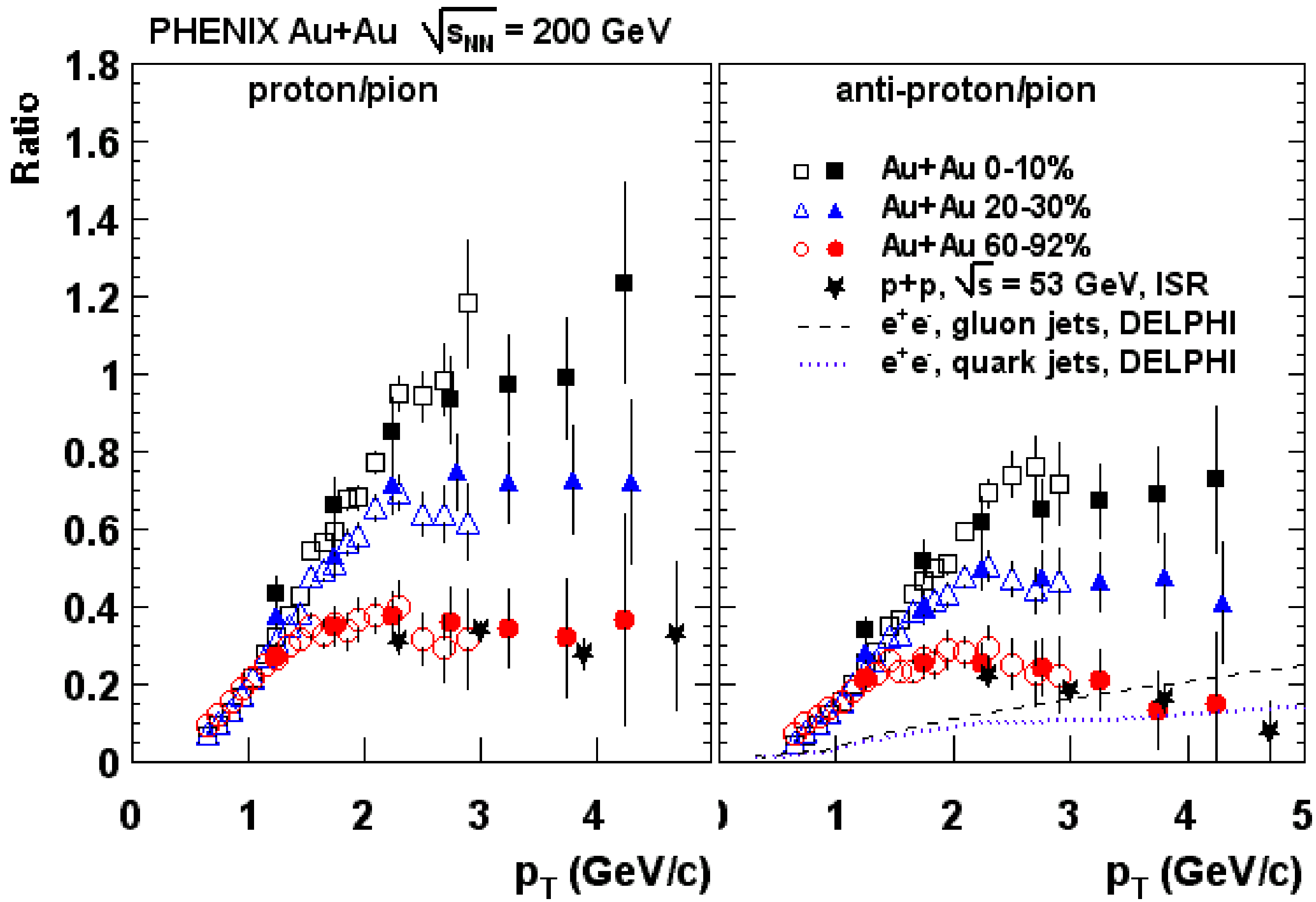
Is Normal Fragmentation Working? We can check particle composition.

Expectation from high-energy p+p data (ISR) is that mesons will dominate at Pt>2GeV/c



Particle composition at high P_T in RHIC A+A is very different!

- $p/\pi \sim 1$ at high p_T for central collisions
- In peripheral collisions, $p/\pi \sim 0.4$

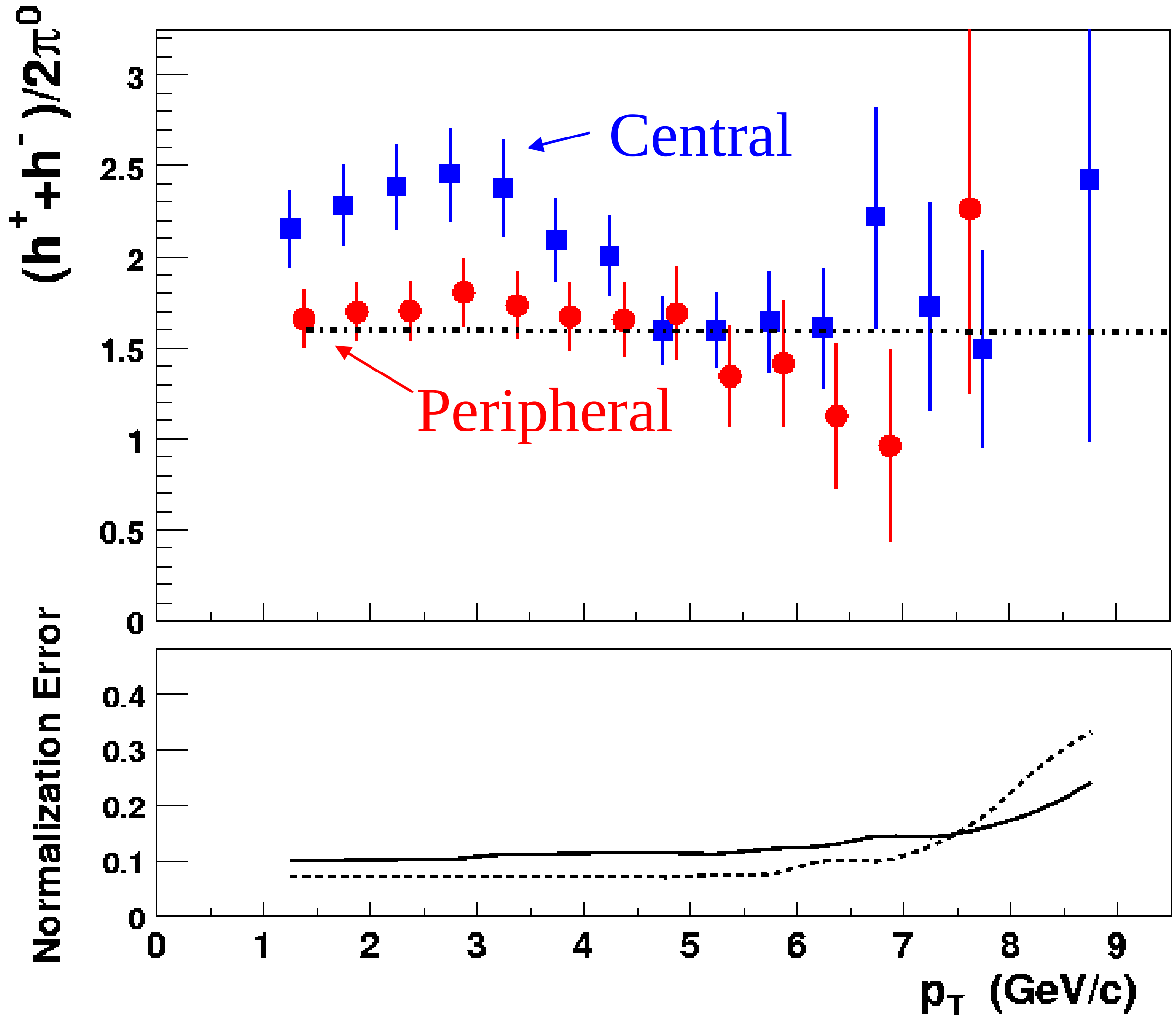


We can measure particle ratios out to highest P_T

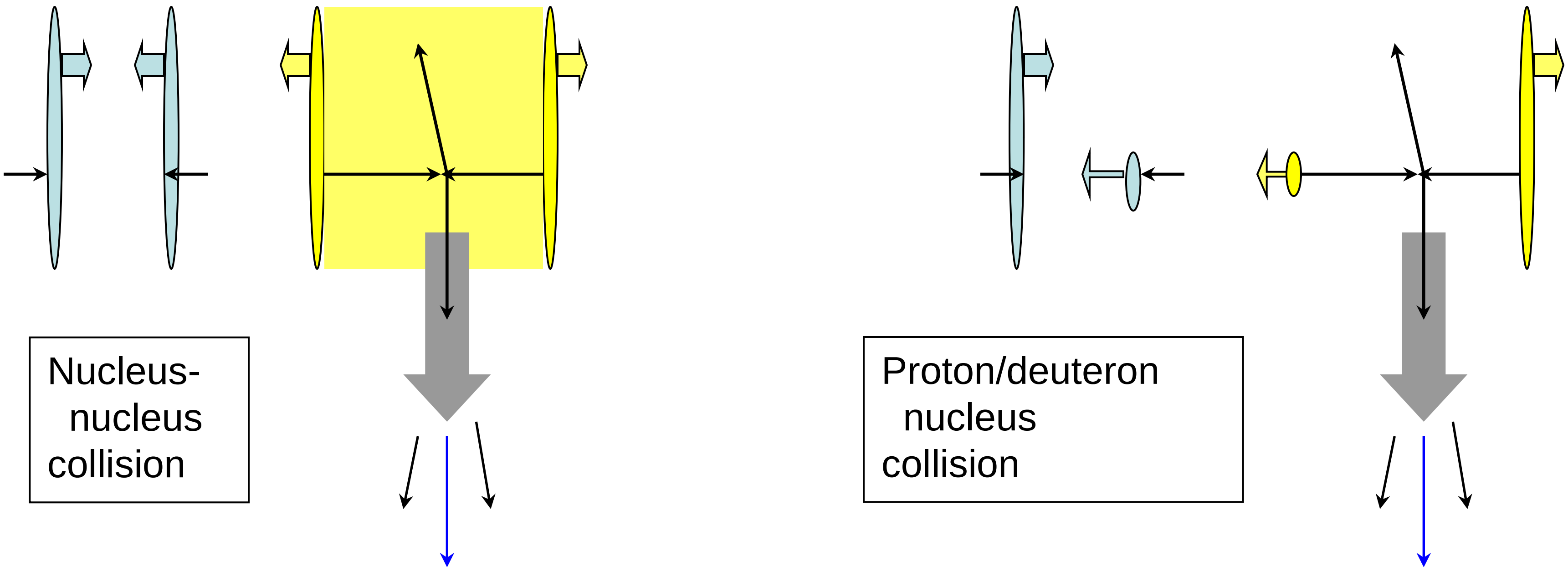
$(h^{+}+h^{-})/2\pi^{0}$ ~ 50% greater in central than peripheral at mid p_T

Cannot be sure yet, but seem to be recovering normal fragmentation for P_T > 5 GeV/c

“Extra” protons appear only in a limited PT range? Are they due to non-fragmentation sources?

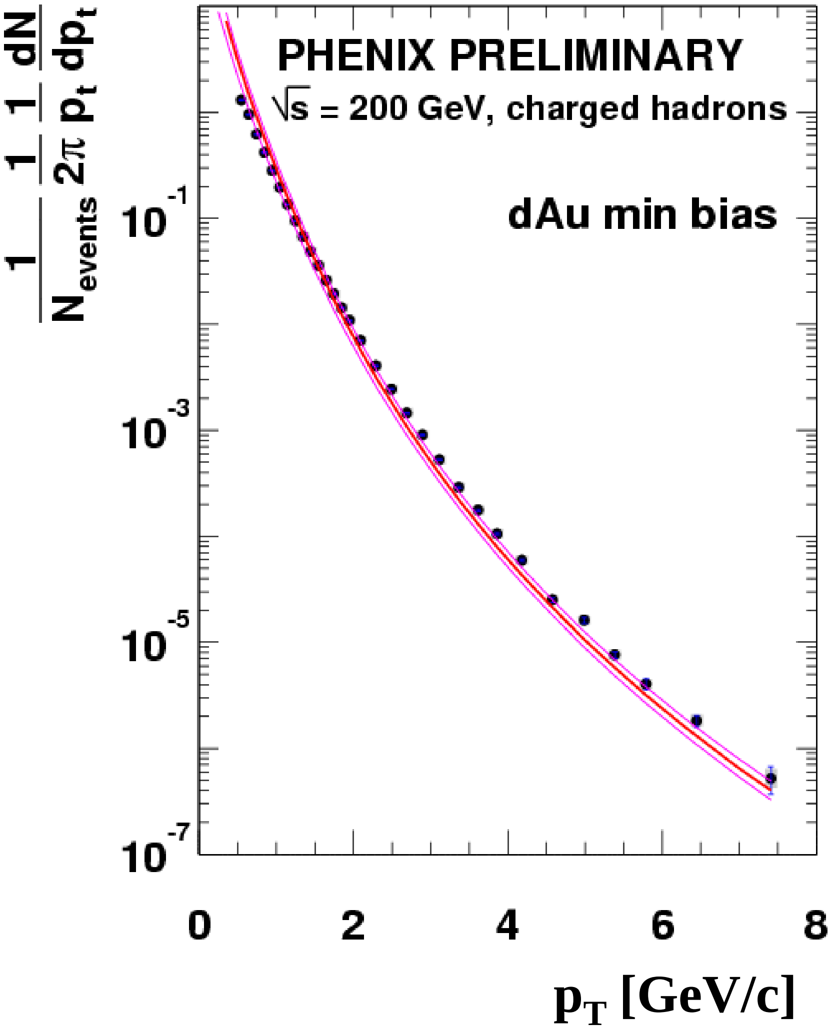


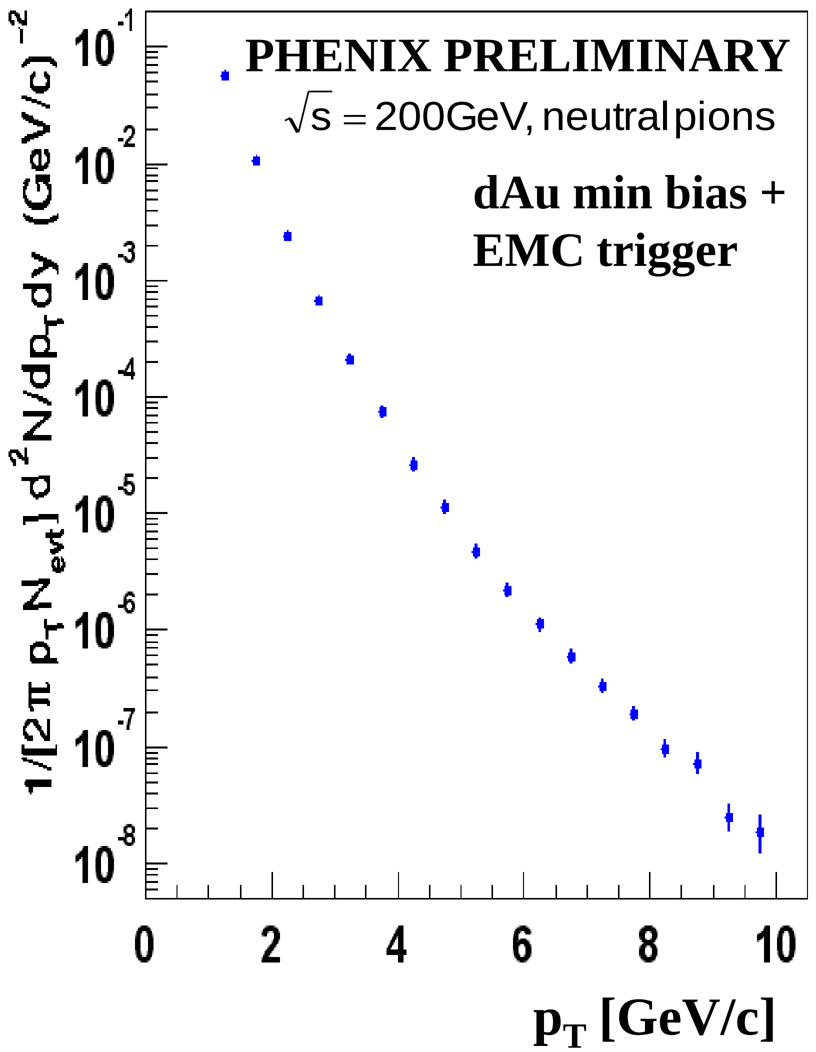
p+A and d+A: The control experiments



Nuclear effects **other than a dense medium** are known to affect hadron spectra (e.g. shadowing, Cronin effect) in p+A and d+A collisions, which do not have a created medium. Could these other influences be causing the suppression of high-P_T hadrons in Au+Au collisions? **If so**, then we should also see strong suppression of high-P_T hadrons in d+Au collisions.

High P_T Spectra in d+Au Collisions

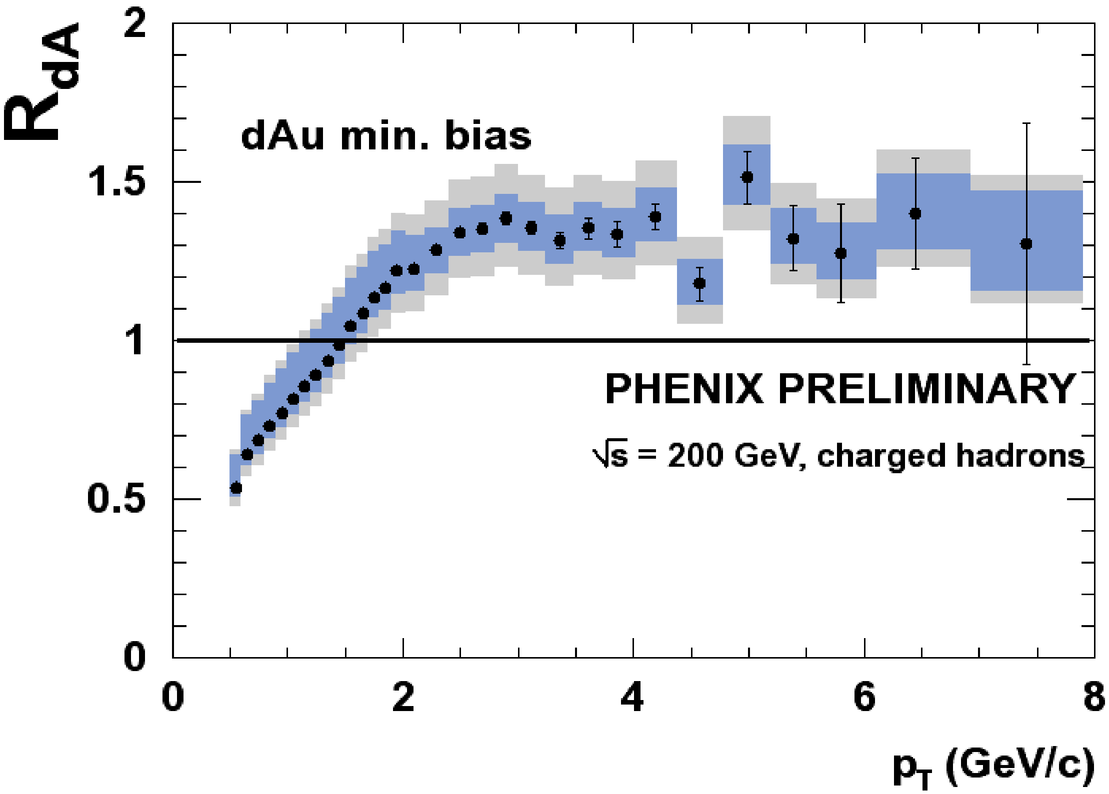




Charged Hadrons R_{AA} for d+Au: $\mathbf{R_{dA}}$

- Charged hadron are measured with tracking detectors in two independent arms

- Cronin type enhancement relative to binary scaling

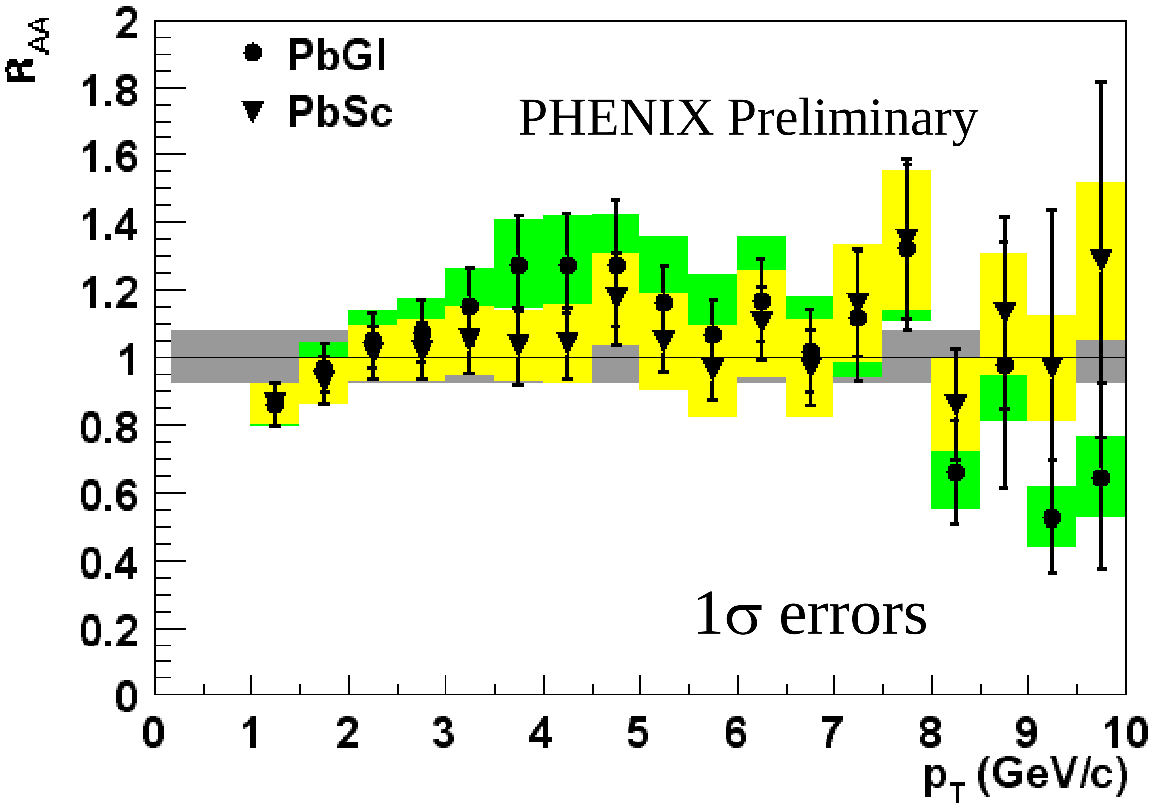


Neutral Pion R_{AA} for d+Au: $\mathbf{R_{dA}}$

Neutral pions are measured with 2 independent Calorimeters – PbSc and PbGl

- 2 results agree within errors

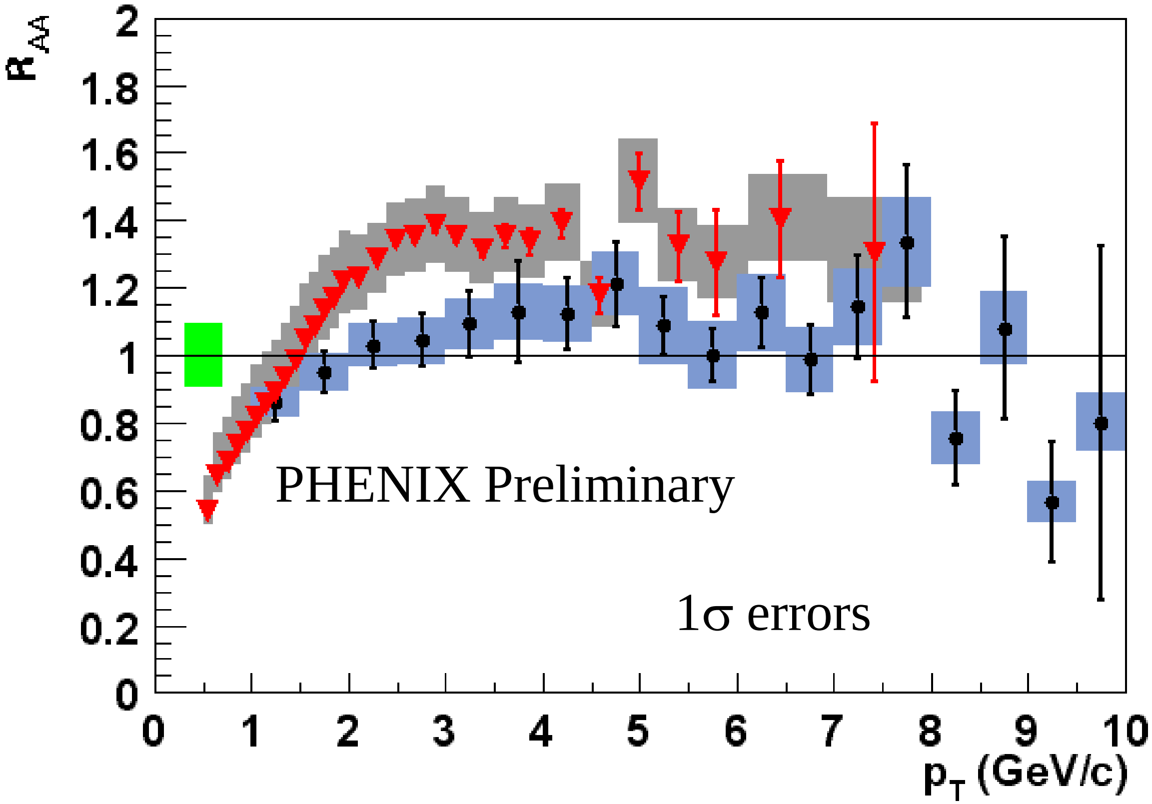
- Not suppressed relative to binary scaling



R_{dA} for charged hadrons compared to π^0

"Cronin" enhancement more pronounced in the charged hadron measurement

Possibly a larger effect in protons at medium p_T



Generally confirm that nuclear effects other than created medium <u>cannot</u> be responsible for hadron suppression in Au+Au

Hard-Scattering in PHENIX: Conclusions

1) Hard-scattered partons act as a built-in QCD probe of the hot, dense medium created in A+A collisions.

2) Observing the emerging partons as high-P_T leading hadrons, we see a strong suppression in central A+A collisions; suggestive of parton energy loss in medium (not conclusive).

3) Particle ratios very different from normal fragmentation in $2<P_T<5$ Gev/c; proton excess clearly visible. Is fragmentation modified? Or is there an alternate source of baryons?

4) Control experiment d+Au results show no strong suppression of high-P_T hadrons. Strongly indicative that suppression effect in A+A must be due to created QCD medium.

Backup slides

Suppression in Inclusive Photons

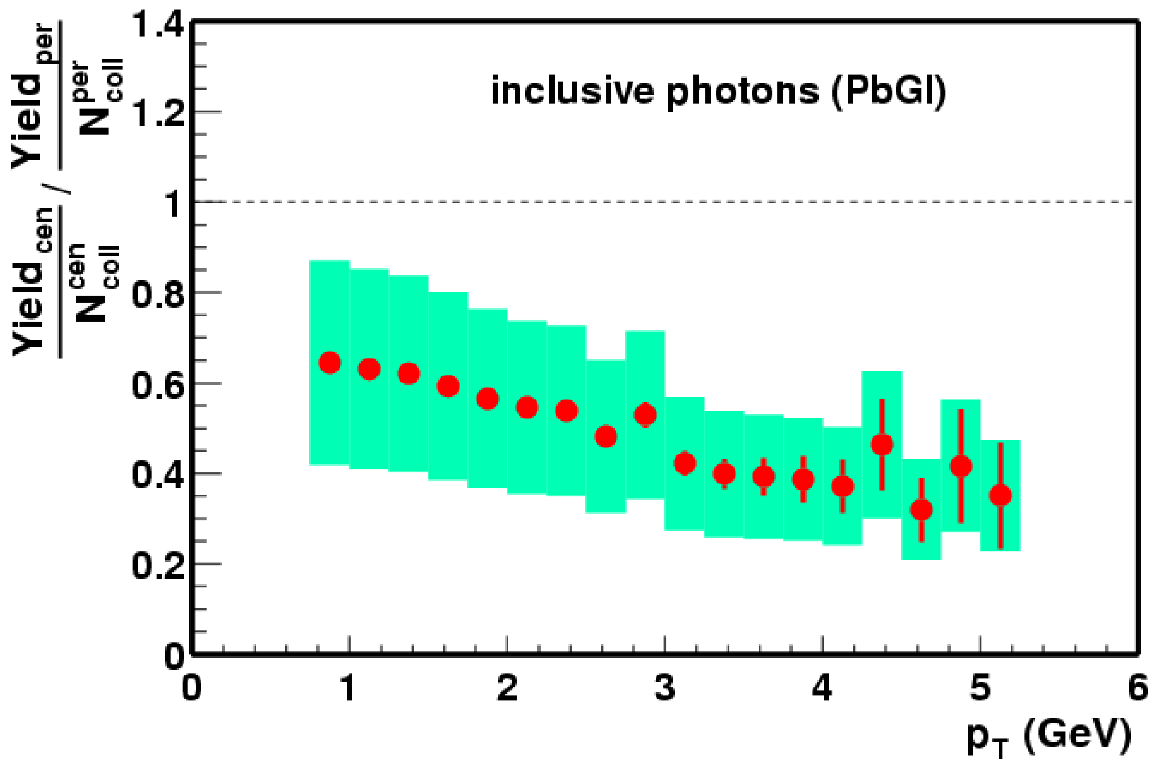
S.Mioduszewski

$$\frac{\mathbf{Yield}_{\mathbf{central}} / \langle \mathbf{N}_{\mathbf{binary}} \rangle_{\mathbf{central}}}{\mathbf{Yield}_{\mathbf{peripheral}} / \langle \mathbf{N}_{\mathbf{binary}} \rangle_{\mathbf{peripheral}}}$$

Photons (primarily from π^0 decays) also show suppression

→ Not an artifact of extraction of π^0 peak yield

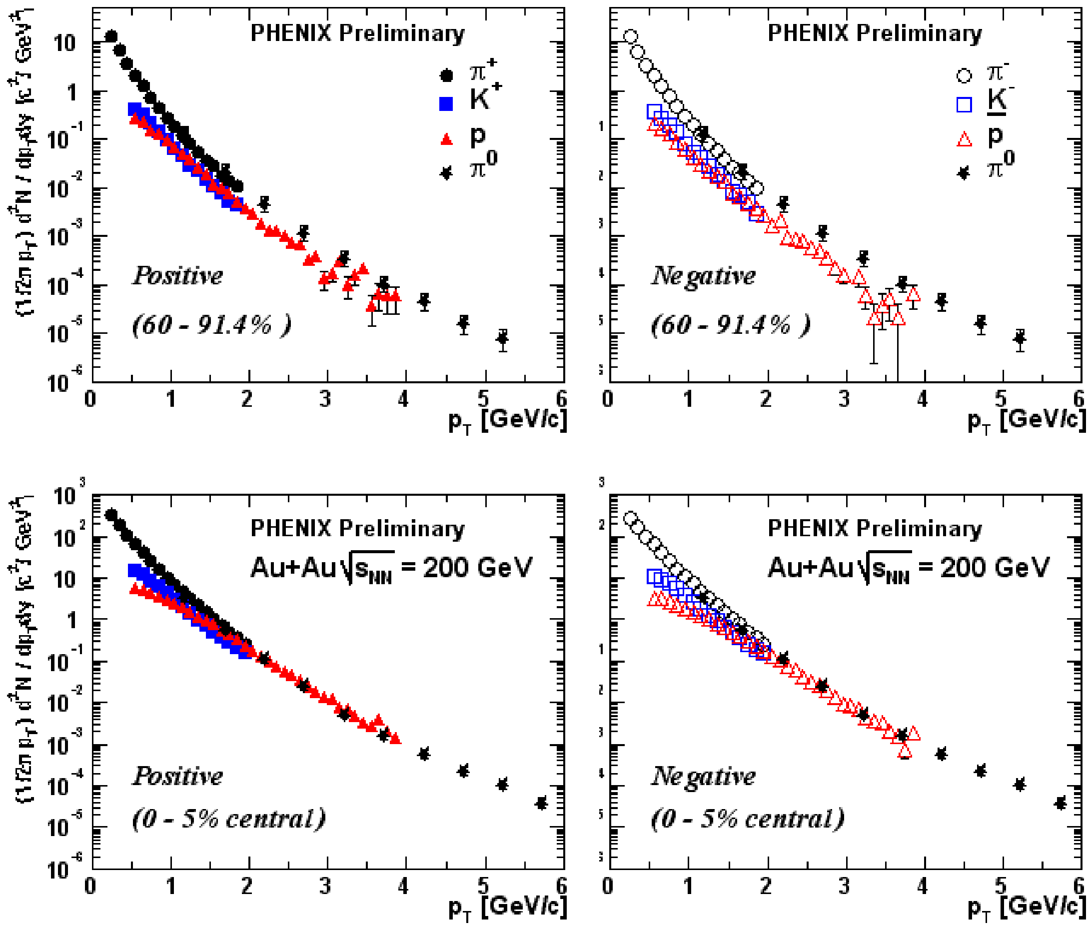
Klaus Reygers talk



Hadron Composition in RHIC A+A

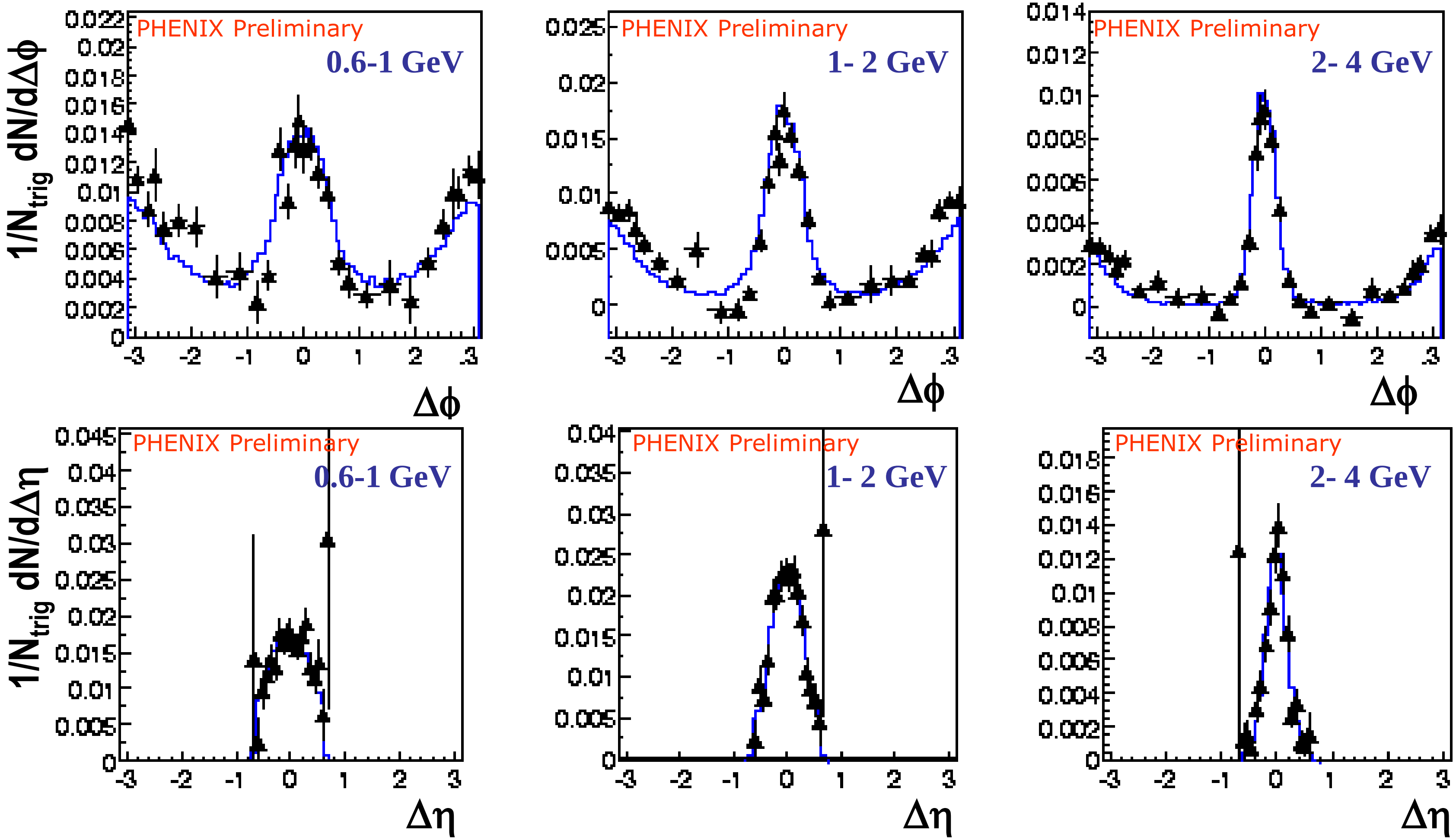
At RHIC, however, we observe that baryons, not mesons, dominate at Pt>2GeV/c in central collisions.

Are (anti-)baryons coming from non-fragmentation process?



J. Velkovska DNP ‘02

Excess Above Flat Background, p-p



•Data points (black) are background subtracted and acceptance corrected.

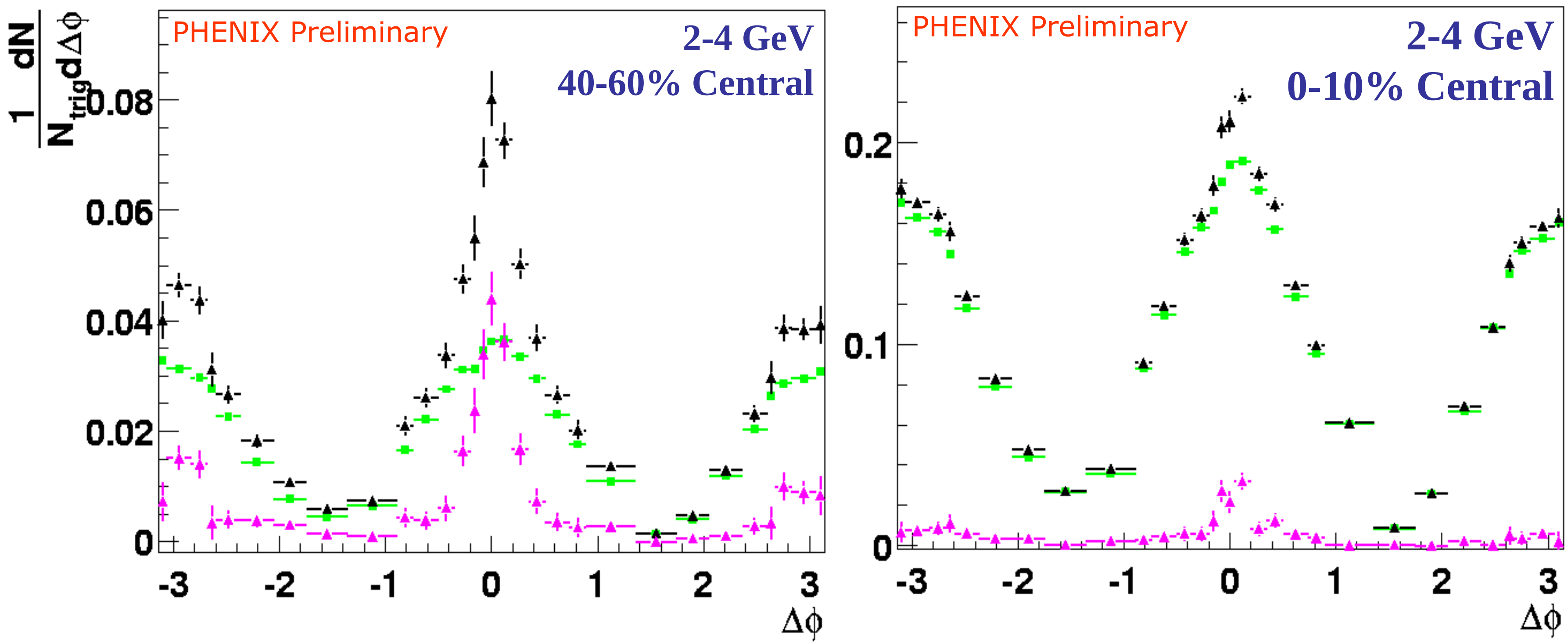
•Blue is the PYTHIA curve * a_{pythia} * <ε>

M.Chiu

Excess from Flat Bkg, Au-Au

M.Chiu

black = associated charged particles, green = mixed, purple = subtracted



- In AuAu collisions there is a statistically significant excess from a flat distribution at all centralities and all pt bins.
- So what is that excess? Try both PYTHIA only and also PYTHIA + elliptic flow contribution.

Fitting Pythia + $2v_{ch}v_{trig}\cos(2\phi)$, pt dependence

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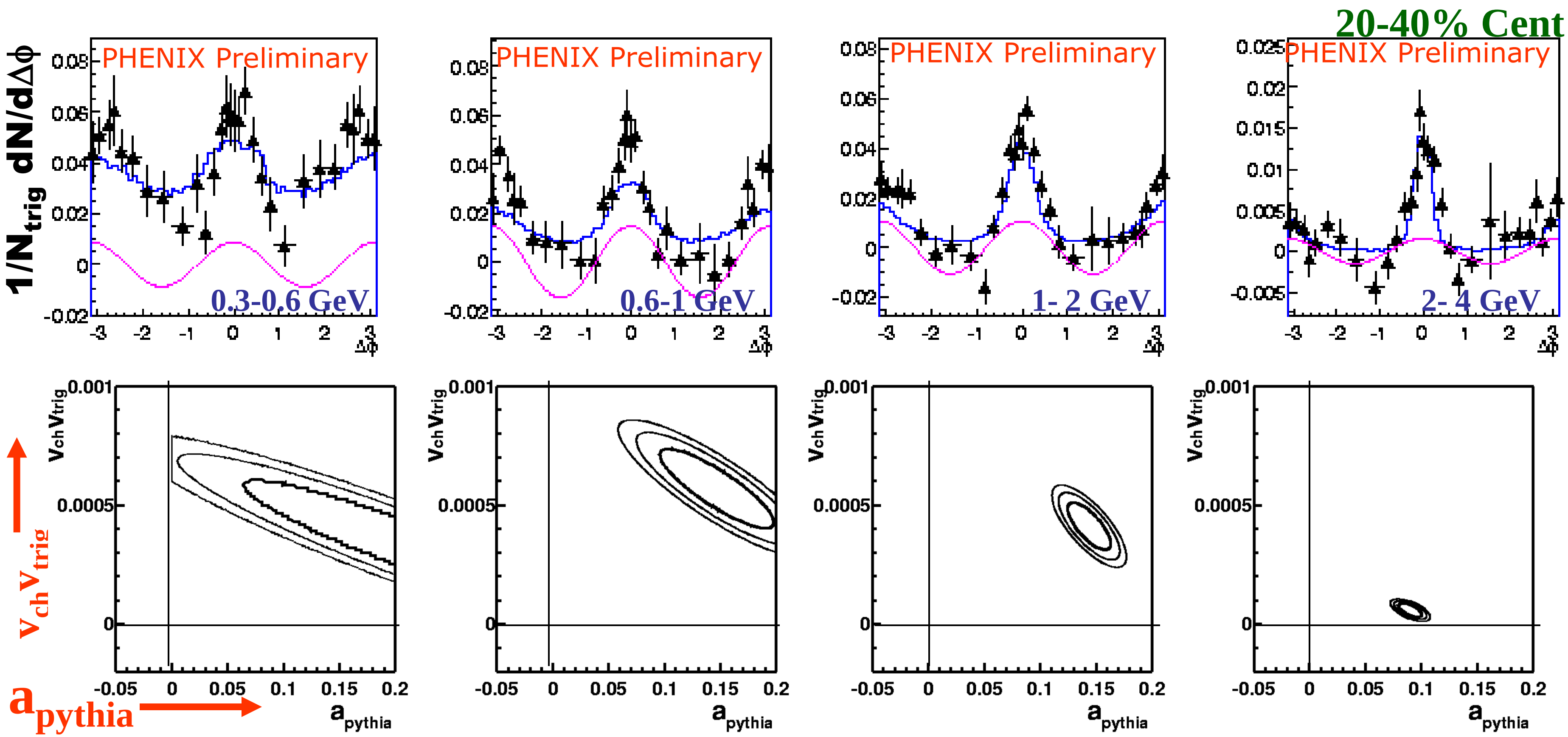

•For lower pt, ambiguity between the contribution from the elliptic flow component and the jet-like component.

•At higher pt (2 GeV and above), the jet-like component dominates over any elliptic flow component.